EP0609012

Publication Title:

Method for manufacturing a thermal ink-jet print head.

Abstract:

An ink fill slot 18 can be precisely manufactured in a substrate 12 utilizing photolithographic techniques with chemical etching, plasma etching, or a combination thereof. These methods may be used in conjunction with laser ablation, mechanical abrasion, or electromechanical machining to remove additional substrate material in desired areas. The ink fill slots may be appropriately configured to provide the requisite volume of ink at increasingly higher frequency of operation of the printhead.

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number : **0 609 012 A2**

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number : **94300395.4**

(51) Int. Cl.[5] : **B41J 2/16**

(22) Date of filing : **19.01.94**

(30) Priority : **25.01.93 US 9151**

(43) Date of publication of application :
03.08.94 Bulletin 94/31

(84) Designated Contracting States :
DE FR GB IT

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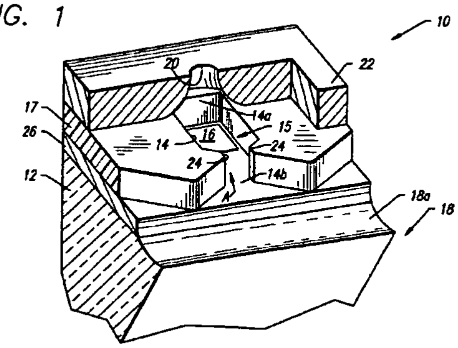
(54) **Method for manufacturing a thermal ink-jet print head.**

(57) An ink fill slot **18** can be precisely manufactured in a substrate **12** utilizing photolithographic techniques with chemical etching, plasma etching, or a combination thereof. These methods may be used in conjunction with laser ablation, mechanical abrasion, or electromechanical machining to remove additional substrate material in desired areas. The ink fill slots may be appropriately configured to provide the requisite volume of ink at increasingly higher frequency of operation of the printhead.

FIG. 1



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CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is related to application Serial No. , filed on [PD-190274], entitled "Compound Ink Feed Slot" and assigned to the same assignee as the present application. The present application is also related to application Serial No. , filed on even date herewith [PD-191123], entitled "Anisotropically Etched Ink Feed Slot in Silicon" and assigned to the same assignee as the present application.

TECHNICAL FIELD

The present invention relates to thermal ink-jet printers, and, more particularly, to an improved printhead structure for introducing ink into the firing chambers.

BACKGROUND ART

In the art of thermal ink-jet printing, it is known to provide a plurality of electrically resistive elements on a common substrate for the purpose of heating a corresponding plurality of ink volumes contained in adjacent ink reservoirs leading to the ink ejection and printing process. Using such an arrangement, the adjacent ink reservoirs are typically provided as cavities in a barrier layer attached to the substrate for properly isolating mechanical energy to predefined volumes of ink. The mechanical energy results from the conversion of electrical energy supplied to the resistive elements which creates a rapidly expanding vapor bubble in the ink above the resistive elements. Also, a plurality of ink ejection orifices are provided above these cavities in a nozzle plate and provide exit paths for ink during the printing process.

In the operation of thermal ink-jet printheads, it is necessary to provide a flow of ink to the thermal, or resistive, element causing ink drop ejection. This has been accomplished by manufacturing ink fill channels, or slots, in the substrate, ink barrier, or nozzle plate.

Prior methods of forming ink fill slots have involved many time-consuming operations, resulting in variable geometries, requiring precise mechanical alignment of parts, and typically could be performed on single substrates only. These disadvantages make prior methods less desirable than the herein described invention.

Further, at higher frequencies of operation, the prior art methods of forming ink slots provide channels that simply do not have the capacity to adequately respond to ink volume demands.

Fabrication of silicon structures for ink-jet printing are known; see, e.g., U.S. Patents 4,863,560, 4,899,181, 4,875,968, 4,612,554, 4,601,777 (and its reissue RE 32,572), 4,899,178, 4,851,371, 4,638,337, and 4,829,324. These patents are all directed to the so-called "side-shooter" ink-jet printhead configuration. However, the fluid dynamical considerations are completely different than for a "top-shooter" (or "roof-shooter") configuration, to which the present invention applies, and consequently, these patents have no bearing on the present invention.

U.S. Patent 4,789,425 is directed to the "roof-shooter" configuration. However, although this patent employs anisotropic etching of the substrate to form ink feed channels, it fails to address the issue of how to supply the volume of ink required at higher frequencies of operation. Further, there is no teaching of control of geometry, pen speed, or specific hydraulic damping control. Specifically, this reference fails to address the issue of precisely matching the fluid impedance of every functional nozzle so that they all behave the same.

A need remains to provide a process for fabricating ink fill slots in thermal ink-jet print-heads in which the fluid impedance of every functional nozzle is precisely matched.

DISCLOSURE OF INVENTION

It is an advantage of the present invention to provide ink fill slots with a minimum of fabrication steps in a batch processing mode.

It is another advantage of the invention to provide precise control of geometry and alignment of the ink fill slots to permit precise matching of fluid impedances of each nozzle.

It is a still further advantage of the invention to provide ink fill slots appropriately configured to provide the requisite volume of ink at increasingly higher frequency of operation, up to at least 14 kHz.

In accordance with the invention, an ink fill slot can be precisely manufactured in a substrate utilizing photolithographic techniques with chemical etching, plasma etching, or a combination thereof. These methods may be used in conjunction with laser machining, mechanical abrasion, electromechanical machining, or conventional etch to remove additional substrate material in desired areas.

The improved ink-jet printhead of the invention includes a plurality of ink-propelling thermal elements, each ink-propelling element disposed in a separate drop ejection chamber defined by three barrier walls and a fourth side open to a reservoir of ink common to at least some of the elements, and a plurality of nozzles comprising orifices disposed in a cover plate in close proximity to the elements, each orifice operatively associated with an element for ejecting a quantity of ink normal to the plane defined by each element and through the orifices toward a print

medium in pre-defined sequences to form alphanumeric characters and graphics thereon. Ink is supplied to the thermal element from an ink fill slot by means of an ink feed channel. Each drop ejection chamber may be provided with a pair of opposed projections formed in walls in the ink feed channel and separated by a width to cause a constriction between the plenum and the channel, and each drop ejection chamber may be further provided with lead-in lobes disposed between the projections and separating one ink feed channel from a neighboring ink feed channel. The improvement comprises forming the ink fill slot and the drop ejection chamber and associated ink feed channel on one substrate, in which the ink fill slot is partially formed by anisotropic etching of the substrate, employing chemical and/or plasma etching. The dimensions of the ink fill slot relative to the ink feed channel may be precisely controlled to aid in fluid tuning of the pen.

The ink fill slot position can be controlled to within about 20 μm of the hydraulic limiting orifice (the area between the lead-in lobes) and can be modulated in depth as the slot extends to minimize air bubble trapping.

The frequency of operation of thermal ink-jet pens is dependent upon the shelf or distance the ink needs to travel from the ink fill slot to the firing chamber, among other things. At higher frequencies, this distance, or shelf, must also be fairly tightly controlled. Through photochemical micromachining, this distance can be more tightly controlled and placed closer to the firing chamber. Etching can be from the frontside, backside, or both. A combination of etch processes can allow a range of profiles of the ink fill slot and shelf. This process can be used instead of, or in conjunction with, conventional "mechanical" slotting procedures to enhance performance or allow batch processing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a resistor situated in a firing chamber formed from a barrier layer, an ink feed channel fluidically communicating with the firing chamber, and an ink fill slot for supplying ink to the ink feed channel, in accordance with the invention;

FIG. 2a is a top plan view of the configuration depicted in FIG. 1 and including adjacent resistors and ink feed channels, in which the shelf length is a constant dimension as measured from the entrance to the ink feed channel;

FIG. 2b is a view similar to that of FIG. 2a, but depicting an equalized shelf length that follows the contours of the barrier layer;

FIG. 3 is a top plan view of a portion of a printhead, showing one embodiment of a plurality of the configurations depicted in FIG. 2A;

FIG. 4 is a cross-sectional view of the resistor configuration of FIG. 3, showing the results of anisotropic etching of a <100> oriented silicon substrate;

FIG. 5 is a similar view as FIG. 4, but with a <110> oriented silicon substrate;

FIG. 6 is a cross-sectional view equivalent to FIGS. 4 or 5 in which the ink-feed slot is produced by abrasive or laser micromachining; and

FIG. 7, on coordinates of pen frequency in Hertz and shelf length in micrometers, is a plot of the dependence of pen frequency as a function of shelf length for a specific drop volume case.

BEST MODES FOR CARRYING OUT THE INVENTION

Referring now to the drawings where like numerals of reference denote like elements throughout, FIG. 1 depicts a printing or drop ejecting element **10**, formed on a substrate **12**. FIGS. 2a and 2b depict three adjacent printing elements **10**, while FIG. 3 depicts a portion of a printhead **13** comprising a plurality of such firing elements and shows a common ink fill slot **18** providing a supply of ink thereto. Although FIG. 3 depicts one common configuration of a plurality of firing elements, namely, two parallel rows of the firing elements **10** about a common ink fill slot **18**, other configurations employed in thermal ink-jet printing, such as approximately circular and single row, may also be formed in the practice of the invention.

Each firing element **10** comprises an ink feed channel **14**, with a resistor **16** situated at one end **14a** thereof. The ink feed channel **14** and drop ejection chamber **15** encompassing the resistor **16** on three sides are formed in a layer **17** which comprises a photopolymerizable material which is appropriately masked and etched/developed to form the desired patterned opening.

Ink (not shown) is introduced at the opposite end **14b** of the ink feed channel **14**, as indicated by arrow "**A**", from an ink fill slot, indicated generally at **18**. Associated with the resistor **16** is a nozzle, or convergent bore, **20**, located near the resistor in a nozzle plate **22**. Droplets of ink are ejected through the nozzle (e.g., normal to the plane of the resistor **16**) upon heating of a quantity of ink by the resistor.

A pair of opposed projections **24** at the entrance to the ink feed channel **14** provide a localized constriction, as indicated by the arrow "**B**". The purpose of the localized constriction, which is related to improve the damping of fluid motion of the ink, is more specifically described in U.S. Patent 4,882,595, and forms no part of this invention.

Each such printing element **10** comprises the various features set forth above. Each resistor **16** is seen to be set in a drop ejection chamber **15** defined by three barrier walls and a fourth side open to the ink

fill slot **18** of ink common to at least some of the elements **10**, with a plurality of nozzles **20** comprising orifices disposed in a cover plate **22** near the resistors **16**. Each orifice **20** is thus seen to be operatively associated with an resistor **16** for ejecting a quantity of ink normal to the plane defined by that resistor and through the orifices toward a print medium (not shown) in defined patterns to form alphanumeric characters and graphics thereon.

Ink is supplied to each element **10** from the ink fill slot **18** by means of an ink feed channel **14**. Each firing element **10** is provided with a pair of opposed projections **24** formed in walls in the ink feed channel **14** and separated by a width **"B"** to cause a constriction between the ink fill slot **18** and the channel. Each firing element **10** may be provided with lead-in lobes **24a** disposed between the projections **24** and separating one ink feed channel **14** from a neighboring ink feed channel **14'**.

The improvement comprises a precision means of forming the ink fill slot **18** and associated ink feed channel **14** on one substrate **12**. In the process of the invention, the ink fill slot **18** is extended to the pair of lead-in lobes **24a** of each firing chamber, either at a constant distance from the entrance to the ink feed channel **14**, as shown in FIG. 2A, or at an equalized distance from the contour formed by the barrier layer **17**, as shown in FIG. 2B. The ink fill slot **18** is extended by means of extension **18a** toward the lead-in lobes **24a**, using precise etching, described in greater detail below, to controllably align the ink fill slot relative to the entrance to the ink feed channel **14**, indicated at **"A"**.

In FIG. 2A, the extended portion **18a** of the ink fill slot **18** terminates at a constant distance from the center-line of the ink fill slot, very close to the lead-in lobes **24a**. Use of precise etching, described below, permits a shorter shelf length, S_L, to be formed; this shelf length is shorter than that of a presently commercially available pen used in Hewlett-Packard's DeskJet® printer, which extends to the edge of the ink fill slot **18**. The shorter shelf length permits firing at higher frequencies than presently commercially available pens. While the fluid impedance of the pen imparted to the ink is reduced compared to that in the commercially available pens, thereby resulting in improved performance, it is not substantially constant from one resistor heater **16** to the next.

In FIG. 2B, the extended portion **18a** of the ink fill slot **18** follows the contour of the barrier wall **17** defining the lead-in lobes **24a**, providing an equalized shelf length S_L. This equalized shelf length provides a substantially constant fluid impedance to the ink in the pen, which results in improved pen performance.

In accordance with the invention, the extended portion **18a** of the ink fill slot **18** is precisely manufactured in a substrate **12** utilizing. photolithographic techniques with chemical etching, plasma etching, or a combination thereof. These methods may be used in conjunction with laser micromachining, mechanical abrasion, or electromechanical machining to remove additional substrate material in desired areas.

Representative substrates for the fabrication of ink fill slots **18** in accordance with the invention comprise single crystal silicon wafers, commonly used in the micro-electronics industry. Silicon wafers with <100> or <110> crystal orientations are preferred. Three methods of ink fill slot fabrication consistent with this invention are detailed below. Typical resultant structures are shown in FIGS. 4C, 5C, and 6C.

In one embodiment, depicted in FIGS. 4A-D, the following steps are performed:

1. Mask the silicon wafer **12** to protect areas not to be etched. Thermally grown oxide **26** is a representative etch mask for silicon.
2. Photo-define openings in the etch mask using conventional microelectronics photolithographic procedures to expose the silicon on the secondary (back) surface to be removed in the desired ink flow channel areas.
3. Etch part way into the silicon substrate from the back surface through the exposed areas of the openings to form the ink fill slots **18**, using anisotropic etchants to provide the desired geometric characteristics of the ink flow channels.
4. Etch into the front surface (a) to connect with the ink fill slots **18** and (b) to extend the ink fill slots to the entrances of the ink feed channels formed in the barrier layer **17**, forming portion **18a**. The barrier layer **17** and defined drop ejection chamber **15** and ink feed channel **14**, along with resistor heater **16** and associated electrical traces, are formed in separate steps prior to this step. The etching in this step may be done using any or all of an isotropic etchant, such as dry (plasma) etching.

FIG. 4D is a cross-sectional view of a final structure in which ink is fed from the bottom of the substrate **12**. In the process depicted in FIGS. 4A-D, <100> oriented silicon is employed as the substrate **12**. An oxide film **26**, preferably silicon dioxide, is formed on both surfaces **12a**, **12b** of the substrate and is used to define the ink fill slot **18** to be etched. Alternatively, a silicon nitride film or other masking layer could be used, as detailed in the prior art.

The dielectric **26** on the secondary surface **12b** is patterned prior to formation of the ink fill slot **18**.

The ink fill slot **18** comprises two portions. The first portion, **18'**, is formed by anisotropic etching. Since the anisotropic etching is in <100> silicon, the angle formed is 54.74°, as is well-known. An aqueous solution of KOH, in a ratio of $KOH{:}H_2O$ of 2:1, heated to about 85°C is used for the anisotropic etching. This etchant etches <100> silicon at a rate of about 1.6 µm/minute. As is well-known, the etching action is greatly reduced at a point where the <111> planes in-

tersect, and the <100> bottom surface no longer exists.

The anisotropic etching is stopped part way through the silicon wafer **12**, as shown in FIG. 4A. Next, heater resistors **16** (and electrical traces, or conductors, associated therewith, not shown) are formed on the front surface **12a** of the wafer, as shown in FIG. 4B. The process, which is well-known, comprises forming appropriate layers and patterning them.

The second portion, **18a**, of the ink fill slot **18** is formed by a combination of isotropic and anisotropic etching, either by wet or dry processes, from the primary surface **12'**. This process etches through the dielectric layer **26** on the primary surface **12a** and into the silicon wafer **12** to connect with the previously-etched ink fill slot portion **18'**. The resulting structure is shown in FIG. 4C.

Dry etching in a plasma system may be used to define the second portion **18a**. CF_4 may be used, but other plasma etchants are also available for faster etching of the passivation while still protecting the silicon surface from overetch.

It is this latter etching step that brings the ink fill slot **18** very close to the ink feed channel **14**. The proximity of the ink fill slot **18** to the ink feed channel **14** permits the printhead to be very responsive to demands for ink required at high drop ejection frequencies. Suitable masking is used to form the second portion **18a**; this masking may be configured to permit obtaining either the constant shelf length structure depicted in FIG. 2A or the equalized shelf length structure depicted in FIG. 2B.

The structure is completed, as depicted in FIG. 4D, by the formation of the barrier layer **17** and the orifice plate **22** with nozzles **20** therein.

FIGS. 5A-D represent a similar cross-sectional view of a final structure in which ink is fed from the bottom of the substrate **12**, which in this case is <110> oriented. Here, anisotropic etching may be used to etch part way or all the way through the substrate **10**, using the same etchant as for <100>. The only difference in the process of this embodiment from that depicted in FIGS. 4A-D is the use of silicon of a different crystallographic orientation.

In another embodiment, shown in FIGS. 6A-D, the wafer is processed by known thermal ink-jet processes on the primary surface to form resistors **16** on the surface of the passivating layer **26**. A suitable photodefined masking layer (not shown) is then applied and imaged, exposing the area to be precision etched. Examples of such masking layers include DuPont's VACREL and positive or negative photoresists, such as Hoechst AZ4906 or OCG SC900, respectively. In this case, only the.primary surface, **12a**, needs to be protected by the in-sulating dielectric layer **26**.

Etching is done by well-documented dry processes utilizing $CF_4 + O_2$, SF_6, or a mixture of fluorocarbon and noble gases to form portion **18a**. The etch profile can be controlled by varying operating pressure and/or etcher configuration from reactive ion etching regimes (about 50 to 150 millitorr pressures and about 400 to 1,000 volts effective bias) anisotropic etching to high pressure planar etch regions (about 340 to 700 millitorr pressure and 0 to about 100 volts effective bias) isotropic etching or some subtle and beneficial combination of processes. The main part **18'** of the ink feed slot **18** is then formed by micromachining, such as mechanical abrasion, e.g., sandblasting, or laser ablation, or electromechanical machining from the secondary surface **12b**.

The barrier layer **17** is generally formed prior to the final formation of the main part **18'**, for reasons related to wafer handling (making the wafer stronger) and parts flow (avoiding returning the wafer to the clean room for processing).

The frequency limit of a thermal ink-jet pen is limited by resistance in the flow of ink to the nozzle. Some resistance in ink flow is necessary to damp meniscus oscillation. However, too much resistance limits the upper frequency that a pen can operate. Ink flow resistance (impedance) is intentionally controlled by a gap adjacent the resistor **16** with a well-defined length and width. This gap is the ink feed channel **14**, and its geometry is described elsewhere; see, e.g., U.S. Patent 4,882,595, issued to K.E. Trueba et al and assigned to the same assignee as the present application. The distance of the resistor **16** from the ink fill slot **18** varies with the firing patterns of the printhead.

An additional component to the impedance is the entrance to the ink feed channel **14**, shown on the drawings at **A**. The entrance comprises a region between the orifice plate **22** and the substrate **12** and its height is essentially a function of the thickness of the barrier material **17**. This region has high impedance, since its height is small, and is additive to the well-controlled intentional impedance of the gap adjacent the resistor.

The distance from the ink fill slot **18** to the entrance to the ink feed channel **14** is designated the shelf S_L. The effect of the length of the shelf on pen frequency can be seen in FIG. 7: as the shelf increases in length, the nozzle frequency decreases. The substrate **12** is etched in this shelf region to form extension **18a** of the ink fill slot **18**, which effectively reduces the shelf length and increases the cross-sectional area of the entrance to the ink feed channel **14**. As a consequence, the fluid impedance is reduced; both of the embodiments described above are so treated. In this manner, all nozzles have a more uniform frequency response. The advantage of the process of the invention is that the entire pen can now operate at a uniform higher frequency. In the past, each nozzle **20** had a different impedance as a func-

tion of its shelf length. With this variable eliminated, all nozzles have substantially the same impedance, thus tuning is simplified and when one nozzle is optimized, all nozzles are optimized. Previously, the pen had to be tuned for worst case nozzles, that is, the gap had to be tightened so that the nozzles lowest in impedance (shortest shelf) were not under-damped. Therefore, nozzles with a larger shelf would have greater impedance and lower frequency response.

The curve shown in FIG. 7 has been derived from a pen ejecting droplets of about 130 pl volume. For this pen, a shelf length of about 10 to 50 μm is preferred for high operating frequency. For smaller drop volumes, the curves are flatter and faster.

As described earlier, FIGS. 2A and 2B depict the shelf length (S_L). In the former case, the shelf is at a constant location on the die and therefore the S_L dimension as measured from the entrance to the ink feed channel **14** varies somewhat due to resistor stagger, while in the latter case, the shelf length is equalized, in that it follows the contours of the barrier layer **17**.

INDUSTRIAL APPLICABILITY

The precision etch of the primary surface of the silicon substrate in combination with the anisotropically etch through the secondary surface provides improved ink flow characteristics and is expected to find use in thermal ink-jet printheads. The precision etch may be done by a variety of isotropic etching processes.

Thus, there has been disclosed the fabrication of ink fill slots in thermal ink-jet printheads utilizing photochemical micromachining. It will be apparent to those skilled in this art that various changes and modifications of an obvious nature may be made without departing from the spirit of the invention, and all such changes and modifications are considered to fall within the scope of the invention, as defined by the appended claims.

Claims

1. A method for fabricating ink fill slots **18** for fluidically communicating with ink feed channels **14** in thermal ink-jet printheads **13**, comprising:

    (a) providing a silicon substrate **12** having a <100> or <110> crystallographic orientation and two opposed, substantially parallel major surfaces **12a, 12b**, defining a primary surface **12a** and a secondary surface **12b**;

    (b) forming an insulating dielectric layer **26** on both said surfaces **12a, 12b**;

    (c) patterning said insulating dielectric layer **26** on said secondary surface **12b** to expose underlying portions of said silicon substrate **12**;

    (d) etching part way through said silicon substrate **12** with an anisotropic etchant at said exposed portions to thereby form a portion **18'** of said ink fill slot **18**; and either

    (e1) forming and defining thin film resistor elements **16** and conductive traces on said insulating dielectric layer **26** on said primary surface **12a**;

    (f1) etching from said primary surface **12a** to connect with said portion of said ink fill slot **18'** to thereby completely form said ink fill slot **18** and to extend the portion of said ink fill slot **18** terminating at said primary surface toward said ink feed channels **14** to cause a widening thereof **18a**; and

    (g1) forming a barrier layer **17** on the major surface of said dielectric material **26** and defining openings therein to expose said resistor elements **16** to define a drop ejection chamber **15** and to provide said ink feed channels **14** from each said resistor element **16** to a terminus region **A**, said terminus region **A** fluidically communicating with said ink fill slot **18** for introducing ink from a reservoir to said drop ejection chamber **15**, whereby the shelf length defined by the distance from the entrance to said ink feed channel **14** and said ink fill slot **18** is decreased; or

    (e2) forming a barrier layer **17** on the major surface of said dielectric material **26** and defining openings therein to expose said resistor elements **16** to define a drop ejection chamber **15** and to provide an ink feed channel **14** from each said resistor element **16** to a terminus region **A**, said terminus region **A** fluidically communicating with said ink fill slot **18** for introducing ink from a reservoir to said drop ejection chamber **15**, said ink fill slot **18** precisely defined relative to said terminus region **A**; and

    (f2) micromachining from said secondary surface **12b** to connect with said portion **18'** of said ink fill slot **18** to thereby completely form said ink fill slot **18**, whereby the shelf length defined by the distance from the entrance to said ink feed channel **14** and said ink fill slot **18** is decreased.

2. The method of Claim 1 further comprising providing a nozzle plate **22** with nozzle openings **20**, each nozzle opening **20** operatively associated with a resistor element **16** to define an ink-propelling element **10**.

3. The method of Claim 2 wherein said terminus region **A** is provided with a pair of opposed projections **24** formed in walls in said layer **17** defining

said ink feed channel **14** and separated by a width **B** to cause a constriction in said ink feed channel **14**.

4. The method of Claim 3 wherein each ink-propelling element **10** is provided with lead-in lobes **24a** disposed between said projections **24** and separating one ink feed channel **14** from a neighboring ink feed channel **14**.

5. The method of Claim 4 wherein said ink fill slot **18a** extends to said lead-in lobes **24a**.

6. The method of Claim 5 wherein said extended portion **18a** of said ink fill slot **18** either terminates at a fixed location and constant distance from the centerline of said ink fill slot **18** of follows the contour of said barrier layer **17** to provide an equalized shelf length S_L.

7. The method of Claim 1 wherein said etching through said primary surface **12a** to completely form said ink fill slot **18** in Step (f1) is done by at least one of anisotropic and isotropic etching.

8. The method of Claim 1 wherein said micromachining from said secondary surface **12b** in Step (f2) is done by one of mechanical abrasion, laser ablation, or electromechanical machining.

9. An improved ink-jet printhead **13** including a plurality of ink-propelling elements **10**, formed by any of the methods of Claims 1-8.

10. The ink-jet printhead **13** of Claim 10 wherein said shelf length ranges from about 10 to 50 μm.

FIG. 1

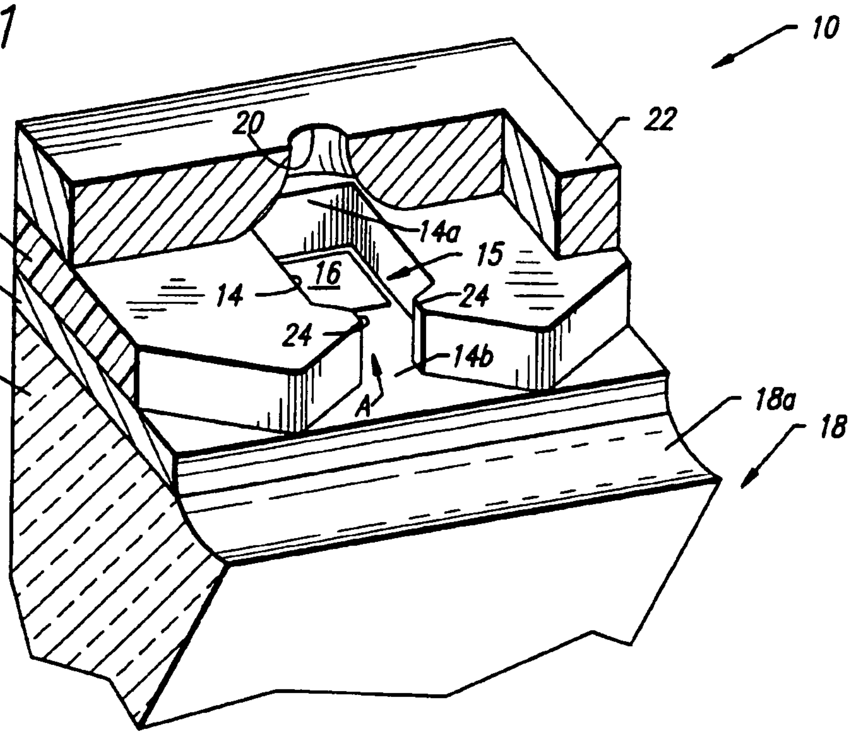

10
20
22
17
26
12
14a
15
16
14
24
24
14b
A
18a
18

FIG. 2a

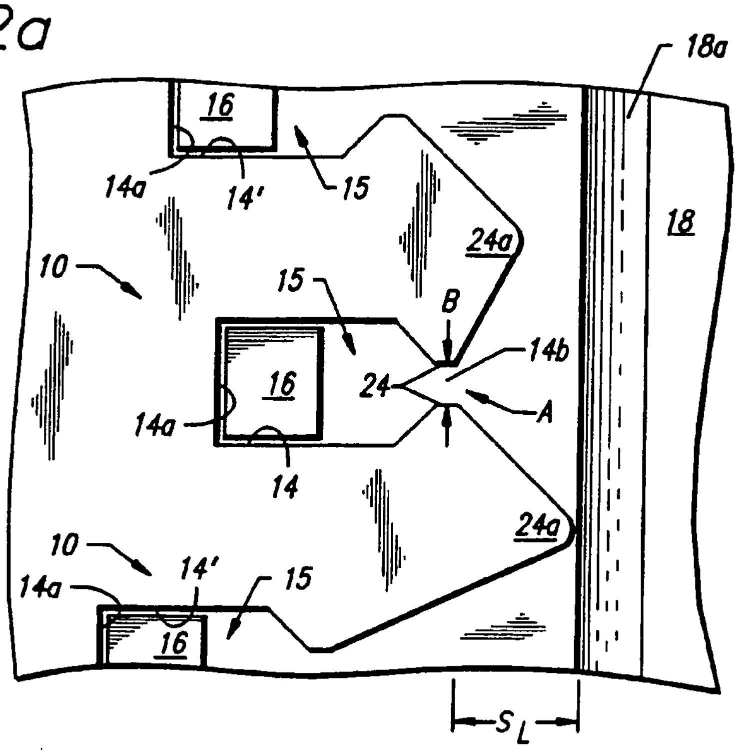
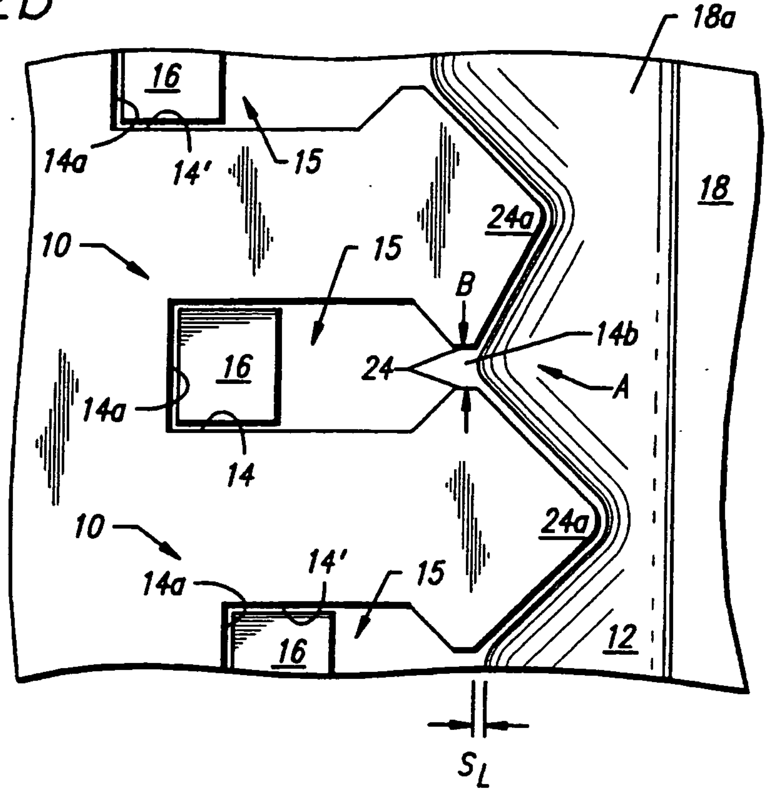
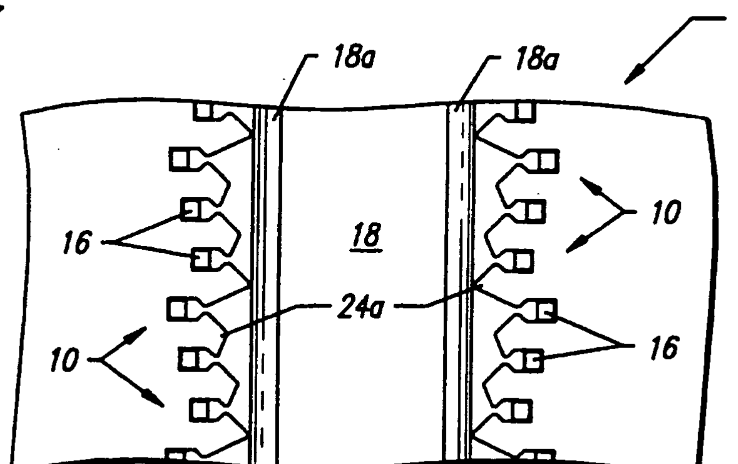

18a
16
14a
14'
15
18
24a
10
15
B
14b
16
24
A
14a
14
24a
10
14'
14a
15
16
S_L

FIG. 2b



18a
16
14a
14'
15
18
24a
10
15
B
14b
16
24
A
14a
14
24a
10
14'
15
14a
16
12
S_L

FIG. 3



13
18a
18a
10
16
18
24a
10
16

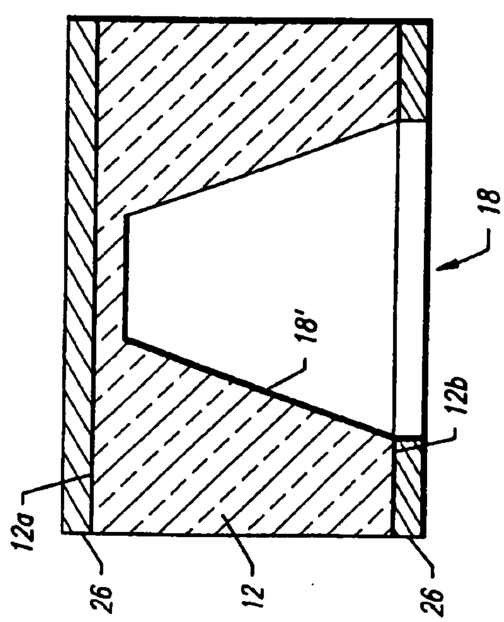


FIG. 4A

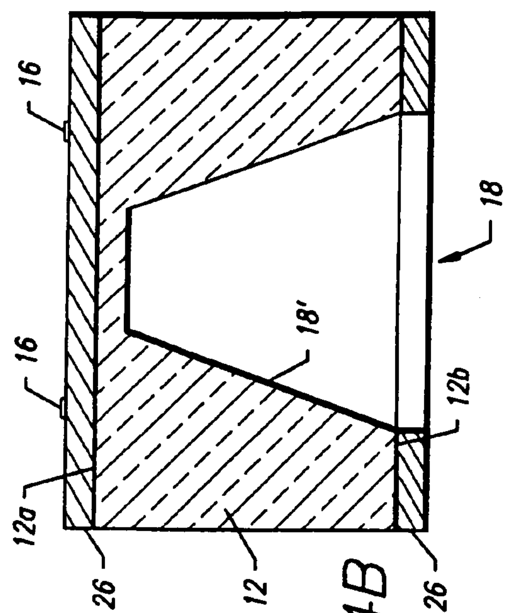


FIG. 4B

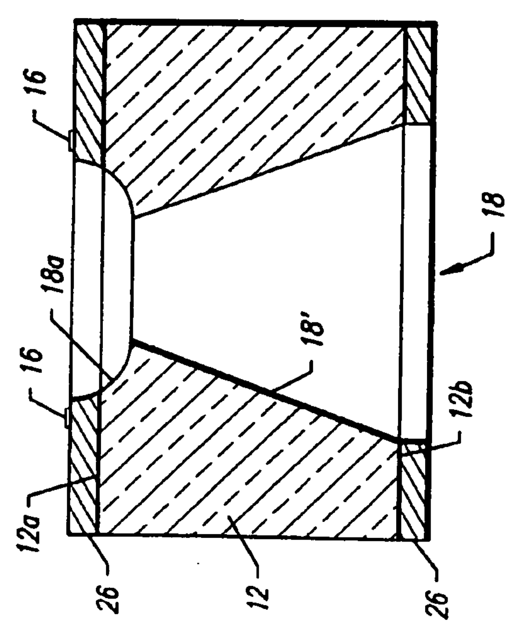


FIG. 4C

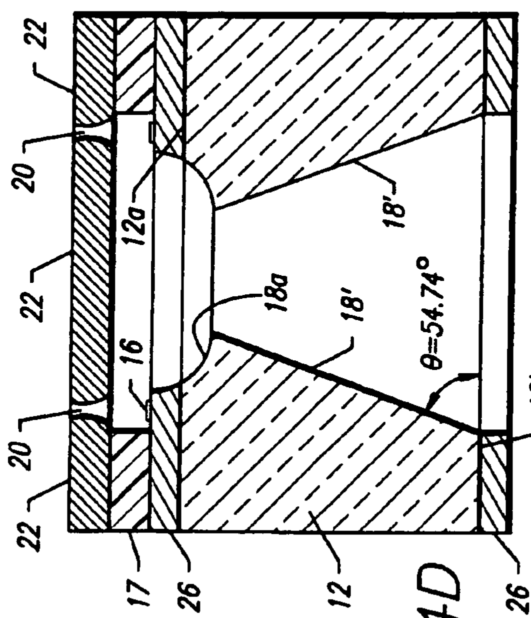


FIG. 4D

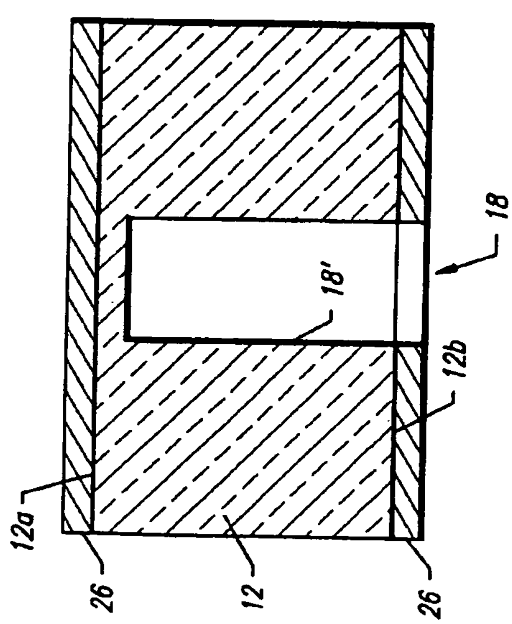


FIG. 5A

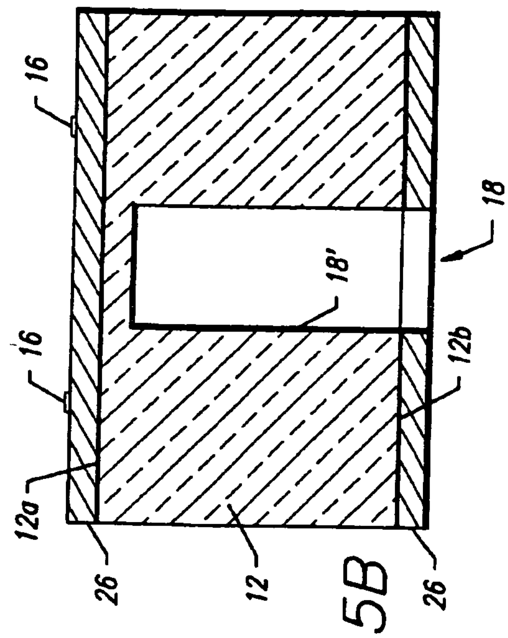


FIG. 5B

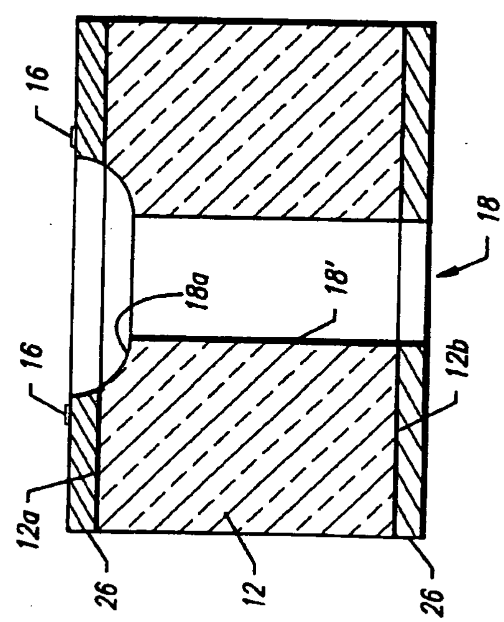


FIG. 5C

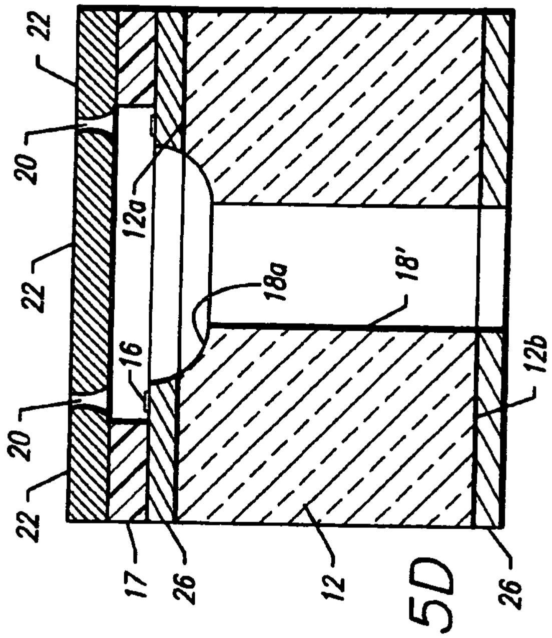


FIG. 5D

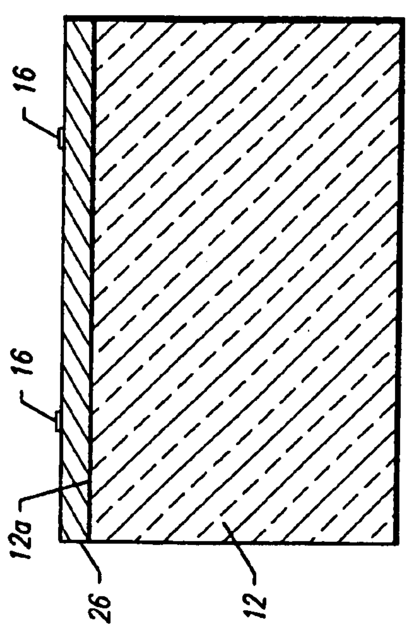


FIG. 6A

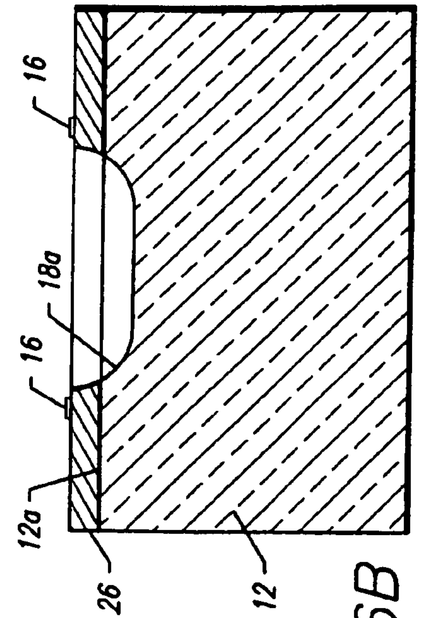


FIG. 6B

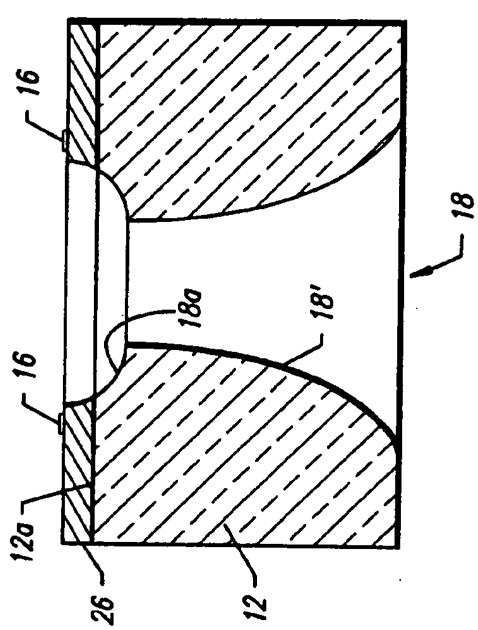


FIG. 6C

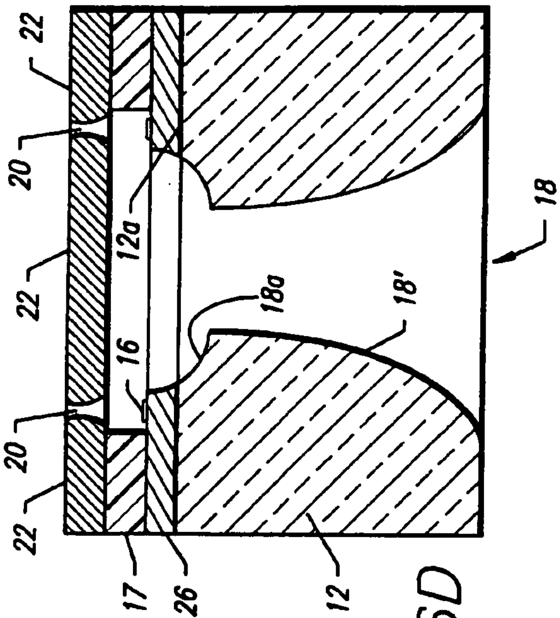
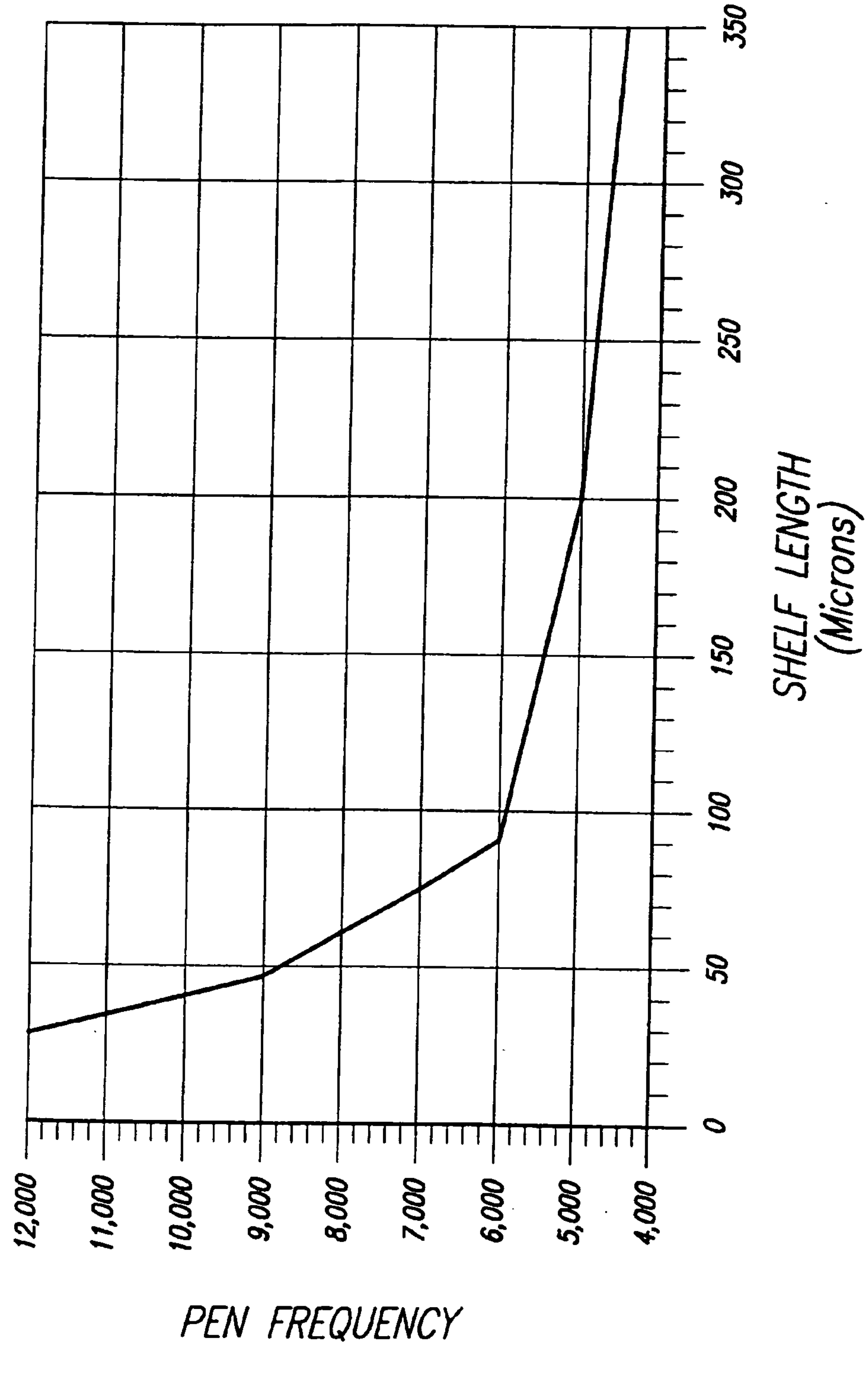


FIG. 6D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(Microns)
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50
100
150
200
250
300
350
PEN FREQUENCY
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000

FIG. 7